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Ultra Starvation Studied in the Spiral Orbit Tribometer

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Spiral orbit tribometry has been used to study the coefficient of friction and electrical contact resistance of two vacuum lubricants in both the flooded system and the regime in which only a few nanoliters (μg) of the lubricant are present, and the latter regime is designated here as ultrastarved. The experiment was supported by the extension to the ultrastarved regime of the recent analysis by Cann and coworkers of contact film thickness as a function of the lubricant volume in the heavily starved regime. The coefficients of friction in the ultrastarved regime were found to be the same as for the flooded system. The contact resistance was found to be zero at the beginning of the tests in the ultrastarved regime. The analysis by Cann and coworkers predicts the absence of a mobile liquid film at the contact in the ultrastarved regime. It is speculated that this persistence of lubrication into the ultrastarved regime is due to the retention of adherent lubricant molecules on the contacting surfaces and the sliding of these molecules over each other. An incomplete coverage of these molecules permits zero contact resistance at the start of the test. The results indicate that ball bearings can operate normally in the ultrastarved regime until the lubricant is consumed by tribochemical reaction.

KEY WORDS

Ball Bearings; Starvation in EHL; Boundary Lubrication Friction; Boundary Lubrication Chemistry; Friction Test Methods

INTRODUCTION

The generation of thin liquid films between the balls and races of highly loaded rolling contacts in the presence of liquid lubricants has been well established both theoretically and experimentally for some time (Hamrock and Dowson *(1)*). As Cann, et al. *(2)* have recently noted, a characteristic of systems with sufficient lubricant present (sometimes referred to as "flooded") is that the film thickness increases with speed. However, if sufficient lubricant is not present, the film thickness decreases with speed, and these systems are referred to as "starved." The study of such starved systems has been the focus of interest for some time. Most recently, the study of Cann, et al. *(2)* (this paper contains references to the earlier literature on starvation) employed optical interferometry in a tribometer to measure film thickness in the contact of the "heavily" or "fully" starved regime, in which only a few tens of microliter (mg) of lubricant is present in the system. Cann, et al. *(2)* observed the transition between a fully flooded condition and one that was characteristic of the heavily starved regime. They were able to fit their data for the film thickness in the starved regime to an expression with a dimensionless starvation degree (SD) parameter. This parameter contains within it the relation to the amount of lubricant present in the system.

A development concurrent with that of Cann, et al. *(2)* has been the use of the spiral orbit tribometer (SOT) (Pepper and Kingsbury *(3)*) to observe the consumption of the liquid lubricant (Pepper and Kingsbury *(4)*). In this rolling contact tribometer, the lubricant is chemically attacked and degraded by reaction with the bearing material and is thus consumed—identified by a rise in the coefficient of friction—during the rolling and spinning of the ball against the race in the SOT. The observation of this tribochemical consumption in the SOT requires that the lubricant charge in the system be restricted to the nanoliter (μg) range. This regime is designated here as "ultrastarved." Although the lubricant regime in which the consumption is observed has been designated as either starved or boundary in the earlier reports on the SOT (Pepper and Kingsbury *(4)*), studies using the SOT would benefit from a better characterization of the lubricant conditions in the contact.

In this report, the tribological properties of two oils used as bearing lubricants in vacuum are studied in the SOT in both the flooded regime where EHL applies and in the ultrastarved regime with the nanoliters of the lubricant in the system. It is shown that "normal" lubrication, in that the system exhibits coefficients of friction of flooded systems, persists into the ultrastarved regime. The Cann, et al. *(2)* analysis developed for the heavily starved regime is extended here into the ultrastarved regime to obtain insight into contact conditions in the ultrastarved regime. Whereas the Cann, et al. *(2)* experimental approach used optical interferometry to determine film thickness, the SOT uses the coefficient of friction (CoF) together with electrical contact resistance. This study can be viewed as an extension of the work of Cann, et al. *(2)* and complementary to it. This study of ultrastarvation in the SOT is also relevant to the operation of ball bearings, since they can be called upon to operate in this regime.

EXPERIMENTAL CONDITIONS

The components of the spiral orbit tribometer (SOT) are depicted in Fig. 1. It has been described before (Pepper and Kingsbury *(3)*). It is basically a thrust bearing with one ball and flat races (plates). It may be regarded as a simplified version of

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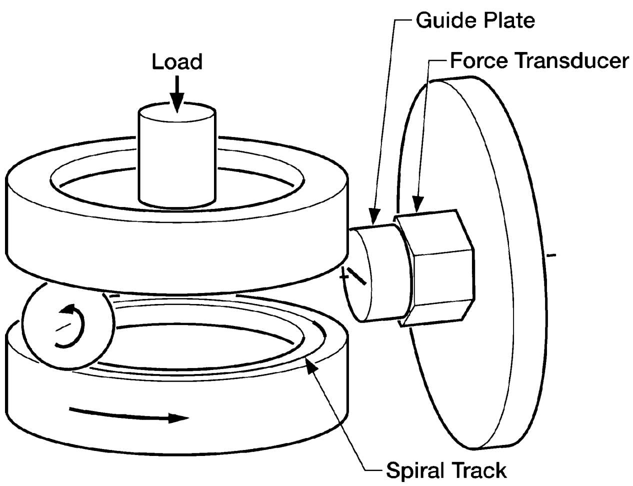

Fig. 1—Components of the spiral orbit tribometer (SOT). The top plate and guide plate are stationary, while the bottom plate rotates to drive the ball.

the usual angular contact ball bearing. One of the plates is stationary and the other rotates to drive the ball into an orbit that is an opening spiral. The ball contacts a "guide plate" at the end of each orbit, which forces the ball back into its initial orbital radius. The ball then exhibits, for a given coefficient of friction (CoF), a stable orbit, repeatedly overrolling the track on both the large plates and the guide plate. The spiral's pitch and the length of the contact on the guide plate increases with the increase of the CoF. A piezoelectric force transducer supporting the guide plate senses the frictional force developed on the ball as it slides on the rotating plate during the contact of the ball with the guide plate. During this contact, the coefficient of friction is obtained from this force (Pepper and Kingsbury *(3)*). The tribometer is housed in a stainless steel chamber that can be evacuated by a turbomolecular pump to $\leq 2 \times 10^{-8}$ Torr. It can be operated either in this vacuum environment or at atmospheric pressure.

The term "spiral," used here only to describe the growth of the ball's orbit as it is driven by the rotating plate, should be taken advisedly. The path of the ball appears to be a spiral in its orbit. In fact, the orbit is not necessarily a mathematical spiral and the term "pitch" will be used here only to denote the radius growth upon one complete orbit. The current understanding of the ball's motion is due to K. L. Johnson *(5)*, who has used the term "creep" for the growth of the ball's orbital radius. At present there seems to be no simple mathematical description of the orbit, so the terms spiral and pitch will be used here for convenience.

The specimens were 440 C stainless steel. Similar results were obtained with 52100 steel. The plates were lapped flat. Their final polish was $R_a < 25$ nm (1 μin) determined by optical interferometry. The balls were commercial 12.7 mm (.5 in.) diameter bearing balls, grade 25, surface roughness <25 nm (1 μin). The combined surface roughness of the ball and the plate was thus always <35 nm (1.4 μin). The final surface cleaning preparation of all ball and plate specimens was by lightly rubbing with aqueous slurries of either alumina or silicon carbide polishing powders, followed by sonication in deionized water. This preparation results in a surface on which water exhibits zero contact angle (spreads) and which exhibits an XPS spectrum a) devoid of impurities other than a small feature due to adventitious carbon and b) in which the Fe^0 feature is clearly evident, indicating a native oxide only a couple of nanometers thick.

The tests reported here were run at a load of 191.3 N (43 lb). An elastic modulus of 207 GPa and a Poisson ratio of 0.3 for the specimens yields an average Hertz contact stress of 1.52 GPa and a Hertz contact diameter of 400 μm. The tests were run at a ball orbit rate of 30 rpm, corresponding to a ball orbit velocity of .071 m/s on the 45.2 mm (1.78 in.) diameter track. All tests were performed at nominal room temperature of 20°C.

Two oils were used in the tests. Krytox 143AC is a perfluoropolyalkylether and is designated here as a PFPE. Pennzane® 2001A is an unformulated multiply alkylated cyclopentane (MAC) hydrocarbon oil and is designated here as a MAC. Both of these oils have very low vapor pressures and are used as lubricants in spacecraft bearings. Their relative degradation rates due to tribochemical attack in the SOT have been reported (Pepper and Kingsbury *(4)*). The properties of these oils relevant to the EHL calculations will be given in the Analysis section below.

The plates were initially clean and only the ball was lubricated in the tests reported here. For the tests in the starved regime, the ball is first weighed and then lubricated by dripping a dilute solution of the lubricant, ~1 μg of lubricant per microliter of solvent (hexane for the MAC or freon for the PFPE) onto the ball rotating on a magnetic chuck. The ball is reweighed after evaporation of the solvent and the lubricant charge is obtained from the weight difference. For the results presented below for the starved regime, 27 μg of PFPE corresponding to 14.5 nL and 13 μg of MAC corresponding 15.5 nL were used. For the tests in the flooded regime, the ball was installed between the specimen plates and neat lubricant was dripped onto it until a visible meniscus at the ball-plate contact was observed while the ball was in motion in the tribometer. The tests in the starved regime were run under vacuum while the tests in the flooded regime were run in air. Even though the tests in the starved regime were run in vacuum, the coefficient of friction is the same when the tests are run at atmospheric pressure—only the number of orbits to failure (lifetime) is extended (Pepper *(6)*).

Three quantities are obtained from a test:

1) The CoF from the force on the ball while in contact with the guide plate.
2) The electrical resistance between the stationary plate and the rotating plate through the two ball-plate contacts in series. This electrical resistance furnishes an indication of whether solid-solid contact may be occurring at the starved lubricated interface. It also can indicate the establishment of an EHL film at the flooded contacts by infinite resistance.
3) The pitch of the ball's orbital spiral. The pitch is obtained (Pepper and Kingsbury *(3)*) from the length of the straight line portion of the orbit during which the ball is in contact with the guide plate and eq. 28 of Pepper and Kingsbury *(3)*. As shown by K. L. Johnson *(5)* (and verified (Pepper and Kingsbury *(3)*) in the SOT), the pitch is directly related to the CoF of the ball in the portion of the orbit during which it is not in contact with the guide plate (~96% of the orbit). The behavior of the pitch

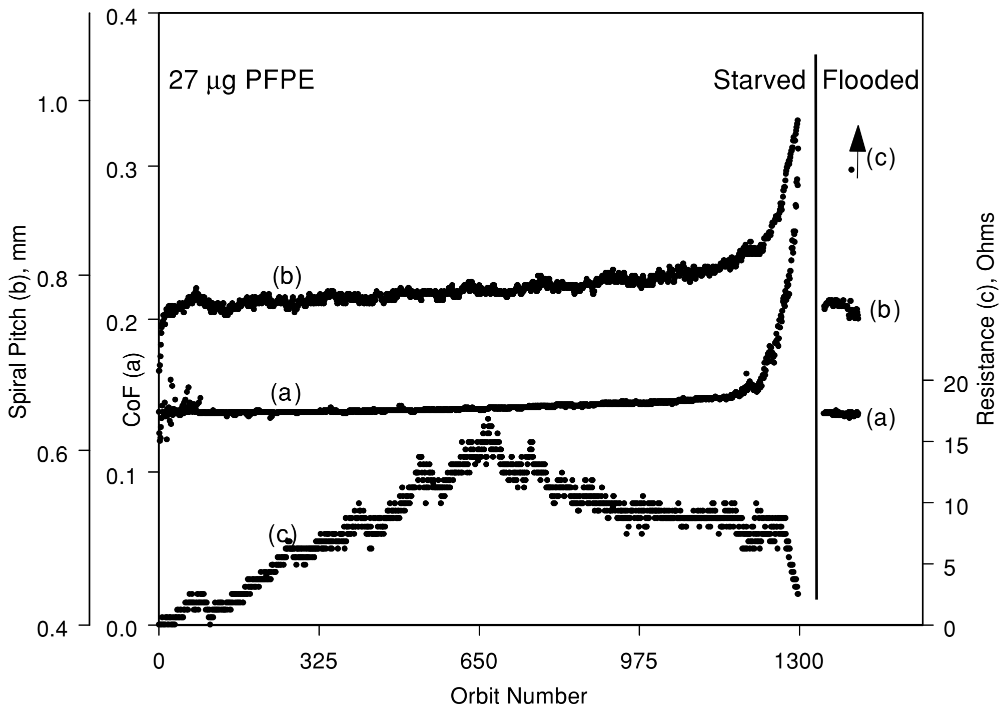

Fig. 2—The CoF (a), spiral pitch (b), and electrical resistance (c) for a test with the PFPE. The left side panel is the record of the values versus the orbit number for a lubricant charge of 27 μg PFPE running in vacuum. The right side panel is the record of the values for 200 orbits of the contact flooded with PFPE running in air.

thus serves as a verification of the behavior of the CoF that is obtained from the force of the ball on the guide plate.

EXPERIMENTAL RESULTS

The results are presented in Figs. 2 and 3. The values of the CoF (a), the spiral pitch (b), and the electrical resistance (c) for a given orbit are plotted against the orbit number throughout the test. The results for these quantities obtained for the MAC are presented in Fig. 3a for the full test and in Fig. 3b for the first 1,000 orbits of this test. Figures 2 and 3a are divided into two panels, with the left side panels showing the results for the test in the starved regime and the right side panels showing the results for running about 200 orbits in the flooded regime.

The results in the starved region for 27 μg of the PFPE and 13 μg of the MAC are considered first. The CoFs (labeled (a) in the figures) for both lubricants are initially rather small and constant and then increase to large values, >0.3. The transition to large CoF has been associated with the total consumption of the lubricant by tribochemical attack (Pepper and Kingsbury *(4)*) and hence the failure of lubrication. Aside from some initial scatter, the CoF for the PFPE exhibits a relatively constant value until an abrupt transition to failure, a behavior that may be the tribological analogue of the incubation period and avalanche of degradation of PFPEs at elevated temperature by metal oxide powders (Zehe and Faut *(7)*; Kasai *(8)*). In contrast to this behavior of the PFPE, the CoF for the MAC gradually increases to failure, which may be due to a more gradual and continuous degradation and loss of MAC lubricant molecules without the incubation/avalanche scenario exhibited by the PFPE. The initial CoF of the MAC is exceptionally smooth as shown in Fig. 3b. The number of orbits to failure for the MAC is much greater than that for the PFPE, in accordance with earlier work (Pepper and Kingsbury *(4)*). Evidently, the MAC is more able to resist the tribochemical attack that is responsible for the more rapid consumption of the PFPE.

The initial values of the CoF for these two cases are given in Table 1. The CoF for the PFPE is greater than the CoF for the MAC. These values obtained recently are in good agreement with those already reported (Pepper and Kingsbury *(4)*).

The spiral pitch for the PFPE in the starved regime exhibits fairly constant values until orbit values at which the CoF abruptly increases. The pitch then abruptly increases as well. The pitch for the MAC is observed in Fig. 3b to be exceptionally constant during the first 1000 orbits of that test and its value is considerably less

TABLE 1—NUMERICAL DATA FROM THE TEST RESULTS SHOWN IN FIGS. 2 AND 3

	PFPE	MAC
Coefficient of friction		
Initial, starved	.138	.077
Flooded	.138	.074
Spiral pitch, mm		
Initial, starved	.76	.45
Flooded	.76	.44
Resistance, ohms		
Initial, starved	0	0
Maximum, starved	17	20
Flooded	∞	Erratic, $>10^4$, $<\infty$

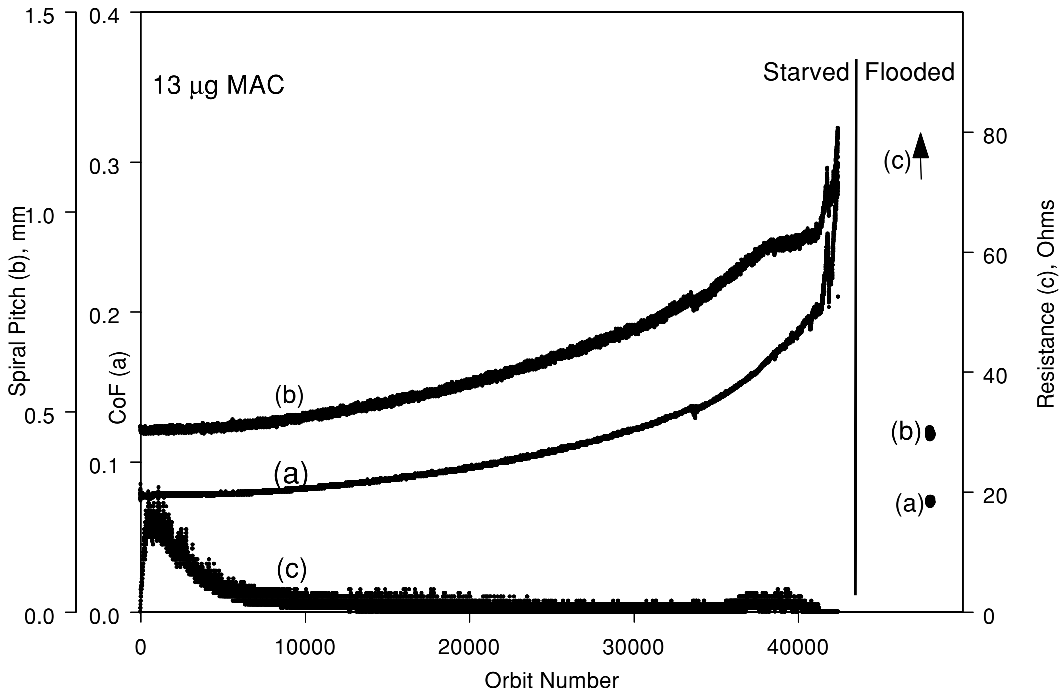

Fig. 3a—The CoF (a), spiral pitch (b), and electrical resistance (c) for a test with the MAC. The left side panel is the record of the values versus the orbit number for a lubricant charge of 13 μg MAC running in vacuum. The right side panel is the record of the values for 200 orbits of the contact flooded with the MAC running in air.

than that for the PFPE. The pitch for the MAC generally increases continually throughout the test as indicated in Fig. 3a, with values that are always less than the values of the pitch for the PFPE. The initial values of the pitch for both tests are indicated in Table 1. The behavior of the pitch generally mimics the behavior of the CoF for both lubricants.

The initial values of the electrical resistance for tests with both the PFPE and the MAC in the starved regime were 0. The resistance is observed to increase to a maximum of a few tens of ohms and then tend toward 0 at the end of lubricant life. These maximum values are indicated in Table 1.

The results for the case of the flooded regime are now presented. Only about 200 orbits were run in this regime because the system is stable and the data do not exhibit the dependence on running time that is evident for the data from the starved regime. The values for the CoF and the pitch are given in Table 1 for both the PFPE and the MAC. These values are very close to the respective initial values found for the starved regime. The electrical resistance of the flooded PFPE system was found to be consistently infinite. However, the electrical resistance for the flooded MAC system was not consistently infinite under the conditions of this test but was instead found to exhibit great variability between tens of kilo-ohms and infinity. Evidently the MAC allowed some solid-solid contact in the flooded regime that was not allowed by the PFPE in this regime.

Although just one set of data has been presented here for each of the lubricants, many tests with each of the lubricants have been performed. The initial values of the CoF, pitch, and the electrical resistance as well as the characteristic dependence of these quantities on the orbit number (up to failure) are highly reproducible

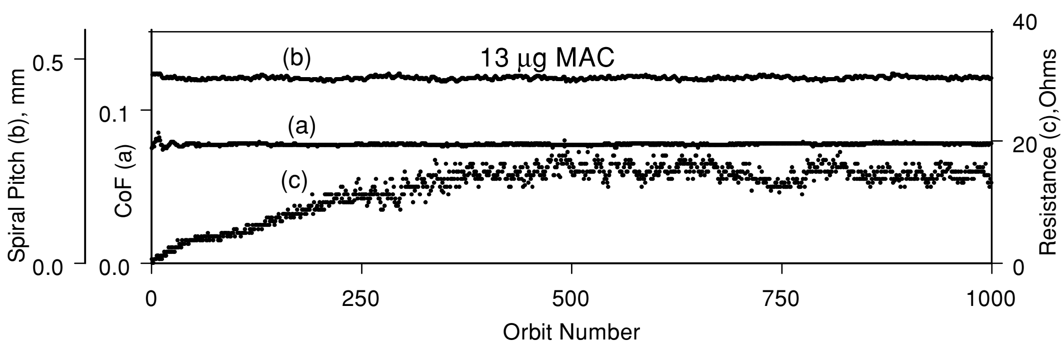

Fig. 3b—The CoF (a), spiral pitch (b), and electrical resistance (c) for the first 1000 orbits of 13 μg MAC running in vacuum.

from test to test of each lubricant. The number of orbits to failure (lifetime of the test) is rather less reproducible. The degree of reproducibility of the CoF and the lifetime may be assessed from the results in Pepper and Kingsbury *(4)*. The finite lifetime is due to the tribochemical attack undergone by the lubricant and the rate of this attack depends on the specific chemical composition of the specimens and the environment in which the test is performed. The least reproducible aspect of the tests is the maximum value of the resistance that is attained throughout a test, although it has been observed to always be less than infinity for tests in vacuum in the starved condition.

ANALYSIS

The recent study of starved lubrication by Cann, et al. *(2)* offers the most current analysis within which the present experimental results from the SOT can be considered. The issue investigated by Cann, et al. *(2)* is whether the lubricant ejected to the sides of a track by a ball can flow back into the track and establish a liquid film before the next pass of the ball. In the SOT, lubricant initially on the ball is transferred to the plates where it is then either a) ejected to the sides of the tracks, b) tribochemically degraded into either volatile species or friction polymer, or c) remains on the track in monolayer concentration available as a lubricant. Although the division of the lubricant between that transferred to the plates and that which remains on the ball is not known, it is instructive to consider the fate of the lubricant if all of it is transferred to the plates and ejected to the sides of the tracks. Here the Cann, et al. *(2)* analysis is used to consider whether the lubricant can flow back into the track and contribute to the establishment of a film observable in the sense of Cann, et al. *(2)*

Cann, et al. *(2)* based their analysis on observations from a tribometer that determines film thickness in the contact with optical interferometry, while the SOT principally determines the coefficient of friction. Their tribometer is similar to the SOT in that both employ rolling contact of a single ball loaded onto a flat plate with restricted lubricant volume available to the system. The tribometers differ, first, in that the SOT captures the ball between two plates instead of loading the ball on only one plate. Second, the entire surface of the ball is exercised in the SOT (Pepper and Kingsbury *(3)*) while only a great circle on the ball is used in the tribometer in the Cann, et al. *(2)* study. Thus there is more complete use of the lubricant in the SOT. It is considered that the similarities warrant the application of the Cann, et al. *(2)* analysis to the experimental results presented here. The Cann, et al. *(2)* analysis is used here to obtain a calculated film thickness in the SOT, which lacks an experimental thickness determination.

The physical basis of the Cann, et al. *(2)* analysis is due in part to Chiu *(9)* and Kingsbury *(10)*, who introduced the idea that, upon each ball pass, the lubricant is ejected from and then reflows back into the track of the system. Cann, et al. *(2)* studied such a starved system and, by varying the system's load, speed, temperature, and the lubricant volume, obtained an expression for h_c, the central film thickness in the contact. The Cann, et al. *(2)* expression for the liquid film thickness is employed here to obtain a prediction for the film thickness that would be established under the present conditions. The Cann, et al. *(2)* expression for

TABLE 2—MATERIAL PROPERTY AND TEST VALUES. THE DENSITY, VISCOSITY, AND PRESSURE–VISCOSITY COEFFICIENT ARE GIVEN FOR 20°C.

Specimen elastic modulus	207 GPa (30×10^6 psi)
Specimen Poisson ratio	.3
System load	191 N (43.0 lb)
Contact width, a	400 μm
Entrainment velocity, u	.071 m/s
Lubricant density	1.865 g/cm^3 PFPE
	.84 g/cm^3 MAC
Lubricant viscosity, η_0	1.492 Pa-s PFPE
	.252 Pa-s MAC
Lubricant pressure-viscosity	4.3×10^{-8} Pa^{-1} PFPE
Coefficient, α	1.6×10^{-8} Pa^{-1} MAC
Lubricant surface tension, σ_s	.018 N/m PFPE
	.030 N/m MAC
Lubricant volume	14.5 nl 27 μg PFPE
	15.5 nl 13 μg MAC
Lubricant oil height, $h_{oil\infty}$	51.1 nm 27 μg PFPE
	54.6 nm 13 μg MAC

h_c is given in Eq. [1].

$$h_c \,/\, h_{eff} = (1.5/SD)^{1.67} \qquad [1]$$

Here h_{eff} is the central film thickness in the flooded condition and SD is the dimensionless starvation degree parameter.

$$SD = \frac{\eta_0 ua}{h_{oil\infty}\sigma_s} \qquad [2]$$

The central film thickness in the flooded condition (the EHL film central thickness in the piezoviscous-elastic regime) is calculated with eq. 8.41 of Hamrock and Dowson *(1)*. In Eq. [2], η_0 is the oil viscosity at test temperature, u is the entrainment velocity, a is the track width, $h_{oil\infty}$ is the amount of oil in the vicinity of the track, and σ_s is the surface tension of the oils. The values of the material properties in the present study that are used in this equation are listed in Table 2. The values of h_{eff} calculated for both the PFPE and the MAC are listed in Table 3.

The parameter $h_{oil\infty}$ in the analysis is the height of the oil piled up next to the track due to the oil's ejection from the track by the passing ball. It is proportional to the amount of oil in the system and is the link between the study of Cann, et al. *(2)*, which used milligrams (mg) of oil, and the study reported here, which uses micrograms (μg) of oil. As indicated above, all the oil in the SOT system is assumed to be available to the tracks on the plates. The value of $h_{oil\infty}$ is obtained by dividing the volume of lubricant by the area adjacent to the two tracks next to which the lubricant resides. This area is then twice the circumference of a

TABLE 3—CALCULATED VALUES. THE h_{eff} IS CALCULATED FOR THE FLOODED CONTACTS, WHEREAS THE VALUES OF SD AND h_C WERE CALCULATED FOR THE STARVED CONTACTS: 27 μg PFPE AND 13 μg MAC FOR THE LUBRICANT CHARGE IN THE SYSTEM

	PFPE	MAC
h_{eff}	525 nm	94.4 nm
SD	46.1×10^3	4.37×10^3
h_c	1.68×10^{-5} nm	1.55×10^{-4} nm

track times the "width" upon which the lubricant is considered to reside. Although there is some degree of arbitrariness in choosing this "width," the value of 1 mm used here is adopted from Cann, et al. *(2)* The area in the SOT is then found to be 2.84×10^{-4} m^2. The values of $h_{oil\infty}$ are given in Table 2. It is these small values that are responsible for the large values of the starvation degree parameter SD given in Table 3. The calculated values of h_c for the present study are given in Table 3. They are extremely small.

These small values of film thickness may be considered in terms of molecular diameter. The thinnest physical liquid film thickness may be taken as two molecular diameters. Since a molecular diameter is about 1 nm, the thinnest physical liquid film is about 2 nm. A film thickness calculated to be less than this (in the present case, very much less) must be considered unphysical. Evidently, the analysis of Cann, et al. *(2)* has been extended to a regime below which it is not physically valid. Alternatively, one may conclude that their analysis predicts the absence of a physical liquid film at the lubricant amounts under consideration here.

The smallest lubricant loading for which the Cann, et al. *(2)* analysis yields a physical result may be calculated based on a lubricant thickness of 2 nm. For their system, the lubricant volume that yields this lower limit of the liquid film thickness is 1.4 μL, while for the present system it corresponds to 30 mg for the PFPE and 4 mg for the MAC. Cann, et al. *(2)* optically observed liquid films for lubricant volumes $\geq$20 μL and thus were well above the lower physical limit. In the present case of ultrastarvation, the predicted thicknesses in Table 3 are well below the physical limit and thus the absence of a liquid film in this regime is predicted by this analysis, a result that is perhaps intuitive in view of the very small amounts of lubricant considered.

This result indicates that the lubricant transferred from the ball to the plate and ejected to the sides of the track does not flow back into the track and contribute to lubrication. In actuality, not all of the lubricant on the ball is transferred as assumed above. Some remains on the track in monolayer form and some remains on the ball as liquid and is still available for lubrication. As noted before, the precise division of the lubricant between the ball and plate throughout the test is not presently known and remains to be addressed.

DISCUSSION

The regimes of liquid lubricated contacts are usually characterized as EHL, starved, or boundary. In the EHL regime a fluid film separates the solids. A fluid film can also be established in the starved regime. As noted above, such films have been studied by Cann, et al. *(2)* The boundary regime is usually defined by the absence of any liquid film at the contact and the occurrence of solid/solid interfacial sliding. Although the main topic of this report is the ultrastarved regime, it is useful to place it in context by first discussing the results for the flooded contacts.

The contact flooded with the PFPE exhibits infinite electrical resistance, indicating the establishment of an EHL film totally separating the contact surfaces. The minimum film thickness determines the ability of the asperities to break through and establish electrical contact. The minimum PFPE film thickness calculated within the usual EHL formalism, eq. 8.23 of Hamrock and Dowson *(1)*, is 290 nm. Since the combined surface roughness of the specimens is 35 nm, the lambda ratio for the flooded PFPE case is $290/35 = 8.3$. This large value is consistent with infinite resistance due to the separation of the surfaces by an EHL film. The contact flooded with the MAC exhibits high and erratic electrical resistance, indicating that there is appreciable solid/solid asperity contact and thus an absence of complete and continuous separation of the surfaces by an EHL film. The calculated minimum MAC film thickness is 53 nm, a value considerably smaller than that for the PFPE due to the lower viscosity of the MAC and the lambda ratio is $53/35 = 1.5$. This value is small enough to allow breakthrough by asperities to make electrical contact. Thus the electrical resistance of the flooded contacts can be understood on the basis of standard EHL theory.

The CoF obtained here for the flooded contact of the PFPE, .138, is close to values obtained by Spikes *(11)* for this PFPE with a traction type tribometer similar to that used by Cann, et al. *(2)* to study starved film thicknesses. This agreement is important in that it supports the SOT's non-standard method of measuring the friction coefficient. This method operates during the ~4% of the orbit during which the ball contacts the guide plate. The ball executes the spiral during the rest of the orbit and, as noted above, the spiral's pitch is directly related to the CoF of the sliding surfaces within the Hertzian contact between the spinning ball and plate (Pepper and Kingsbury *(3)*). An inspection of the results in Table 1 and the behavior of the spiral's pitch in Figs. 2 and 3 indicates a direct correspondence between the pitch and the CoF measured here, so the implication is, even in the absence of a quantitative theory for the spiral's pitch, that the values of the CoF presented here are the same values that determine the spiral's pitch. This equality between the spiral's pitch in the flooded and ultrastarved cases thus supports the equality of CoFs in the flooded and ultrastarved cases determined by-the-guide plate force. Since the motions of a ball in the usual angular contact ball bearing are, aside from aspects due to the different curvature of the races, entirely similar to the motions of a ball in the portion of the orbit in the SOT out of contact with the guide plate (Kingsbury *(12)*), the CoFs presented here should hold for those in a ball bearing as well.

Turning now to the electrical resistance in the ultrastarved regime, it is seen that the resistance is initially zero, rises to finite values, and then tends to zero again at failure. There is evidently sufficient asperity contact initially to produce zero electrical resistance. This is consistent with the conclusion of the extension of the Cann, et al. *(2)* analysis into the ultrastarved regime that a liquid film cannot be established to separate the surfaces. The capability of measuring electrical resistance is thus a major advantage in confirming the analytic prediction of the lack of a continuous liquid film at the contact. The increase in resistance with successive orbits may be interpreted as the generation of electrically insulating friction polymer due to tribochemical breakdown of the lubricant. The eventual tendency toward zero may be due to displacement of the friction polymer due to high friction forces at failure along with the depletion of lubricant molecules required to generate a replacement friction polymer.

The orbit-to-orbit CoFs for both lubricants are highly repeatable. Thus, even though zero electrical resistance in the ultrastarved regime leads to the expectation of high, noisy friction characteristic of the boundary regime, these contacts can thus be described as lubricated in the usual sense of the term —low, quiet friction, which is a characteristic not usually considered that of the boundary regime. These results may thus prompt a reconsideration of the conceptual basis of the "boundary regime."

The observations discussed here help to characterize the ultrastarved contact conditions in the SOT under which lubricant consumption is evident. However, since the ultrastarved regime has passed from the realm of existing analysis of starved contacts, one can only speculate on the mechanisms responsible for the lubrication of highly loaded ball bearing contacts. In this spirit, the conflicting observations of zero electrical resistance, a calculated absence of a liquid film, and the CoFs characteristic of a lubricated system may be reconciled by considering that a monolayer of the lubricant molecules coats each of the contacting surfaces. Asperity breakthrough leading to zero resistance occurs over a very small fraction of the contact region, a fraction too small to contribute appreciably to the shear strength (friction force) of the contact. Instead, the friction is determined by interchain sliding of one surface lubricant molecule against its counterpart on the mating surface. These lubricant molecules are considered to be attached to the surface and not to constitute an independent mobile liquid film at the contact, in accordance with both the prediction of the Cann, et al. *(2)* analysis extended into the ultrastarved regime and the observation of zero electrical resistance. Friction will depend only on the properties of the lubricant molecule and not on the particular bearing material on which it resides. The lifetime of the lubricant, however, will depend on the bearing material since the molecule is pressed into contact with it to generate tribochemical reaction and attendant lubricant degradation.

It is not very surprising that some lubrication would be present in the ultrastarved regime. However, the numerical equality of the CoF for the flooded and starved regimes was not expected. The concept of friction due to interchain sliding may connect these observations since, as pointed out by Karis and Jhon *(13)*, it is related to work in polymer rheology where the friction between chains determines the rate of the polymer flow (Ferry *(14)*). The term "friction coefficient" in that field relates the interchain shear force to interchain velocity. Further study of the relationship between the CoF in the flooded and starved regimes and their relationship to polymer rheology may be helpful in understanding the numerical equality and physical origin of the friction coefficient in these two very different regimes.

CONCLUSION

The major conclusion of this study is that lubrication persists into the ultrastarved regime. Although a mobile liquid film is not established at the contact in this regime, and there is some solid/solid interfacial contact leading to zero electrical resistance, the contact acts as if there were lubricant molecules adhering to the contact's surfaces. Although this scenario is speculative and requires confirmation by experiment, it may be that interfacial sliding between these molecules determines the contact's CoF, which is found to be the same value as the CoF of the contact in an EHL regime. The persistence of lubrication into the ultrastarved region—i.e., the region in which no liquid film is established and in which the total consumption of the lubricant is eventually evident—has not been well recognized for ball bearing technology. The present results are relevant to the operation of the usual angular contact ball bearings because the SOT *is* a ball in the commonly understood sense of the term. That is, it is a ball captured and loaded between races and driven to execute all the motion present in an angular contact ball bearing. Thus, the usual angular contact ball bearing can be expected to operate normally in the ultrastarved regime, at least until the lubricant is consumed.

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